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ANALYSIS OF AN RRSRM WITH ITS NONLINEAR MAGNETIC PROPERTIES

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ABSTRACT

The behaviour of rolling rotor switched reluctance motors (RRSRM) is strongly determined by the properties and mode of operation of the magnetic field [1]. The rotor is being moved by the magnetic force in the stator, where this magnetic field depends on the varying air gap between the rotor and the stator. The aim of this work is the technical-mathematical description of an RRSRM and its nonlinear magnetic properties.
The highlights of this work describe the motor and its fundamental mode of operation. The properties of the magnetic field determine the overall operation of the RRSRM, as they cause interactions also with the electrical and mechanical domains [2]. Therefore the magnetic field is described and implemented here as a detailed, nonlinear network. The behaviour of a rolling rotor switched reluctance motor is strongly affected by these nonlinearities [3].
For these reasons a multi-physical description is implemented using MODELICA, so an interdisciplinary analysis of the RRSRM is made possible and it provides the basis for future research [4].
Only with an exact technical-mathematical model it is possible to design new drive concepts [5].

Index Terms – Jiles-Atherton, nonlinear magnetic field, Modelica, torque ripple

1. INTRODUCTION

Analysis of electrical machines is a very important area, and modelling and simulation support this action. New design methods allow the investigation of new drive concepts and make it possible to investigate technical systems better [2]. Multi-physical modelling leads to interdisciplinary simulation [6]. Electrical machines consist of electrical, magnetic and mechanical domains, which interact strongly. Therefore the here described analysis of the rolling rotor switched reluctance motor uses multi-physical modelling. The implementation of an RRSRM is based on the fundamental knowledge of the properties of the magnetic field [1]. Therefore the mathematical description and the interactions must be investigated also among other domains [2]. The nonlinear behaviour of the magnetic domain has a massive effect on the performance of the complete drive concept. [7] A complete simulation model should contain electrical and mechanical parts as well. This modelling concept can be used to improve the overall efficiency of electrical machines.

2. BASIC STRUCTURE AND PRINCIPLE OF RRSRM

The Rolling Rotor Switched Reluctance Motor belongs to the category of reluctance motors. Reluctance motors use the principle of the minimisation of the magnetic reluctance or the increasing of the inductance [1].
The fundamental structure of RRSRM is characterised by the moving rotor which is rolling in the stator. This property has strong effects on the applicability of this electrical machine. The important parts and the functional construction of a 4-pole RRSRM are illustrated in Figure 1.

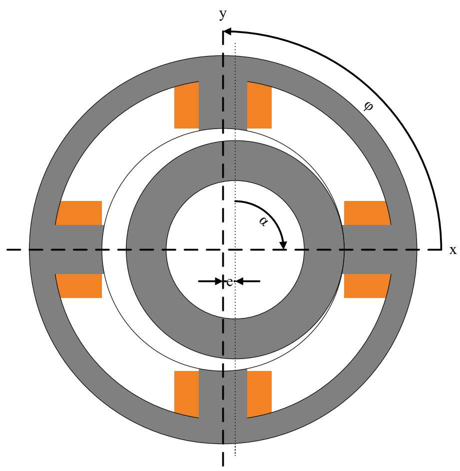

Figure 1 Layout of the RRSRM

The essential diameters of the rotor and stator can be seen here, which are used to customise a gear transmission with possibly high gear ratios. Therefore a rolling rotor switched reluctance motor can be used in a direct drive manner. A salient feature of this electrical machine – having a rotor that has no bearing – characterises it as an RRSRM. This property affects the magnetic field and so the overall behaviour within all available domains, as well. The fundamental construction is characterised by the rolling rotor made of iron and the stator having lumped windings. If the windings are switched alternately, a force can be produced. Here the rotor is moved to the activated coil to reduce the magnetic resistance or to increase the inductance of the lumped winding. The movement of the rotor generates a variable magnetic reluctance within the air gap, so it is a function of the rotor position as is illustrated in Figure 2.

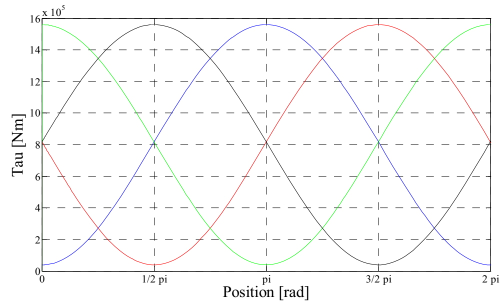

Figure 2 Magnetic Reluctance of Air Gap

This property generates a time varying magnetic field and this creates flux variations which lead to a torque ripple.

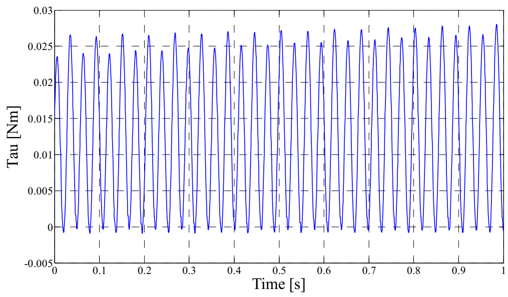

Figure 3 Torque Ripple

This torque ripple is a fundamental characteristic of reluctance motors and a crucial point for the application of these motors [8]. The torque ripple of an analysed 4-pole RRSRM is illustrated in Figure 3. This effect is generated by the concentrated coils. The force is not continuously applied to the rotor.

Furthermore, this varying magnetic field influences the power electronics and the mechanics. These properties have advantages as well as disadvantages which delimit the field of application of this machine [2].

2.1. The Multi-domain Description of RRSRM

The mathematical description of a rolling rotor switched reluctance motor occurs on the basis of following equations which describe the interrelationships between the different domains.

$$u(t) = u_R + u_L(i,\varphi) = R \cdot i + \frac{\partial \Psi(i,\varphi)}{\partial i} \cdot \frac{di}{dt} + \frac{\partial \Psi(i,\varphi)}{\partial \varphi} \cdot \frac{d\varphi}{dt}$$

$$\Phi_{mag} \cdot R_{mag} = u_{mag} = w \cdot i_{elec}$$

$$R_{mag} = f(\varphi_{mech}, i_{elec})$$

The first equation describes the coupling between electrical and magnetic domains. The flux linkage is a function of the rotor position and the supply current derivative with respect to time. The description of the second equation shows the influences between the magnetic voltage and the electrical current with the number of windings. Furthermore, the magnetic field is described on the basis of a reluctance network. The magnetic reluctance network has a nonlinear characteristic and is a function of the rotor position (angle) as it is presented in the last equation [1].

All these equations show that significant domains are highly interconnected and interdependent. Therefore a multi-domain modelling has to be used [6]. For this purpose, the overlapping description of the domains is a fundamental approach to investigate the behaviour and the mode of operation of rolling rotor switched reluctance motors.

2.2. The Description of Magnetic Field

An electrical machine is described as an interconnected system and the mode of operation is based on the phenomena in the magnetic field. Therefore, the magnetic field is an essential part of the analysis of electrical machines [8].

The magnetic field of RRSRM is dependent both on time and rotor position. Consequently, the magnetic fluxes are interdependent. The magnetic flux of one coil is strongly interconnected with the movement of the rotor. Here the reluctance network is changed by the rolling rotor. This time-varying process has an effect on the magnetic flux linkage and consequently, on the operation of the RRSRM [2].

The description of magnetic field can be executed on the basis of analytical equations or numerical models [9]. The analytical method uses network models for the description of the magnetic field as is illustrated in Figure 4. The magnetic reluctance network has the advantage that the description of an electrical machine can be carried out within multiple physical domains. Because of the coupling of the equations within these different domains the simulator is able to solve this system of equations [6].

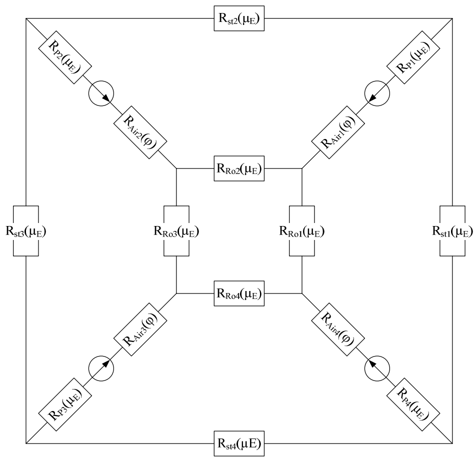

Figure 4 Reluctance Network of RRSRM

The magnetic field of a rolling rotor switched reluctance motor is implemented analytically. There, the magnetic reluctances are described on the basis of Maxwell's equations. This method is based on the physical analogy between the electric and magnetic field as can be seen in Figure 5.

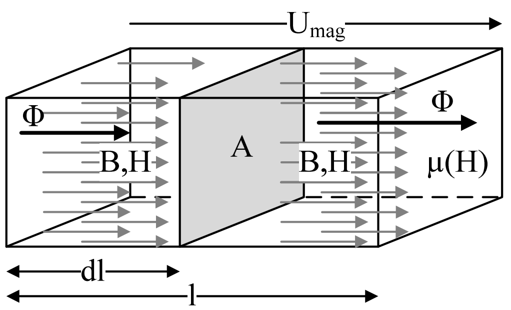

Figure 5 Analytical Description of Magnetic Field

This method describes the magnetic circuit on the basis of magnetic resistances. There, the magnetomotive force and the magnetic flux are analysed. For this purpose, all magnetic elements are modelled as magnetic resistors.

3. NONLINEAR PERMEABILTY OF FERROMAGNETIC RELUCTANCE NETWORK

Electromagnetic phenomena in electrical machines are described by several equations. The nonlinear permeability of ferromagnetic materials is a very important phenomenon. The electromechanical energy conversion is strongly influenced by this property. The magnetic field effects denominate the energy transmission between the different energy domains. Therefore a complex mathematical model is needed for the analysis of electrical machines. If the reluctance network contains a ferromagnetic material the permeability is a characteristic curve with saturation and hysteresis properties. The magnetic flux is a function of the applied magnetic voltage as is illustrated in following equation:

$$\Phi = f\left(U_{mag}\right)$$

The operation of the rolling rotor switched reluctance motor is determined by the magnetic effects and consequently by its nonlinear behaviour. The permeability describes the magnetic conduction of a material. In contrast to the permeability of free space, ferromagnetic materials behave differently [9]. Therefore, the nonlinear description of the magnetic reluctance network is an important aspect of the mathematical model. The comparison between nonlinear and linear characteristics of ferromagnetic material is shown in Figure 6. The characteristic curve of the selected magnetic materials can be different.

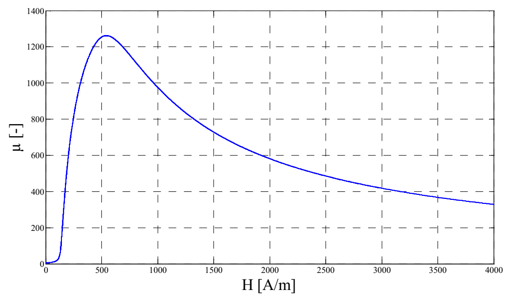

Figure 6 Nonlinear Permeability

This property shows that the permeability is a function of applied magnetic field strength and current density. The magnetic permeability is calculated as the product of the relative permeability and the magnetic permeability in vacuum as is illustrated in the equation below.

$$\mu = \mu_0 \cdot \mu_r$$

where the permeability in vacuum is defined as follows:

$$\mu_0 = 4 \cdot \pi \cdot 10^{-7}$$

The relative permeability defines the magnetic conduction of a material. All this effects have considerable influences on the mode of operation of the rolling rotor switched reluctance motor and must be considered.

4. ANALYTICAL DESCRIPTION OF NONLINEAR PERMEABILITY

The fundamental magnetic field properties are described on the basis of the Weiss-domain-theory. The Jiles-Atherton model was published in 1983. This publication presents a modelling method for hysteresis effects of ferromagnetic materials.

4.1. The Jiles-Atherton Model

The Jiles-Atherton model describes the approach of a real physical process on the basis of differential equations. The intensity of magnetisation in relation to the magnetic field strength is defined in the following equation:

$$B = \mu_0 (M + H)$$

This approach uses the Jiles-Atherton model to define the relation between the applied field strength and the magnetisation. The intensity of magnetisation describes the additional response of the ferromagnetic material to an external magnetic field [7]. There, the magnetisation is defined as a sum of two parts as illustrated below. The reversible component of the magnetisation is described by M_{rev} and the irreversible is described by M_{irr} as is described in the equation below:

$$M = M_{rev} + M_{irr}$$

The base of the Jiles-Atherton model is the modified Langevin equation. This equation represents the anhysteretic process and is a nonlinear function of the effective field H_e as is presented in the following equation.

$$M_{an} = M_S \left(\coth\left(\frac{H_e}{a}\right) - \frac{a}{H_e} \right)$$

where the effective field strength H_e is defined as follow:

$$H_e = H + \alpha M$$

The combination of reversible and irreversible components represents the differential equation for the total magnetisation. This calculation is shown in the equation below:

$$\frac{dM}{dH} = (1 - C)\frac{M_{an} - M}{\delta K - \alpha(M_{an} - M)} + C\frac{dM_{an}}{dH}$$

where δ is a sign function as follows:

$$\delta = sign\left(\frac{dH}{dt}\right)$$

The parameters K, a and α are material constants which are determined by the used ferromagnetic material.

4.2. Modelling of Jiles-Atherton Model

This hysteresis model is described using the language MODELICA and the simulation using the compiler DYMOLA [4] [10]. The results of this Jiles-Atherton implementation are compared to the theoretical description. As it can be seen in Figure 7, the mathematical analysis and the implemented solution show the same results.

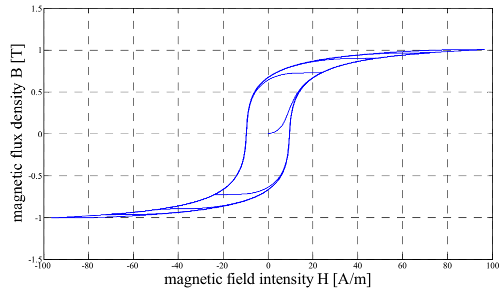

Figure 7 Hysteresis Loop

The description of magnetic behaviour on the basis of the Jiles-Atherton model is suitable for all time variable excitations.

5. ANALYSIS OF AN RRSRM

The mode of operation of a rolling rotor switched reluctance motor is dominated by the magnetic field and its properties. Therefore, the nonlinear behaviour of magnetic material is modelled on the basis of the above described Jiles-Atherton model. The fundamental part of the dynamic simulation of electrical machines is the saturation of the magnetic flux density [5]. This comparison of linear and nonlinear behaviour is illustrated in Figure 8.

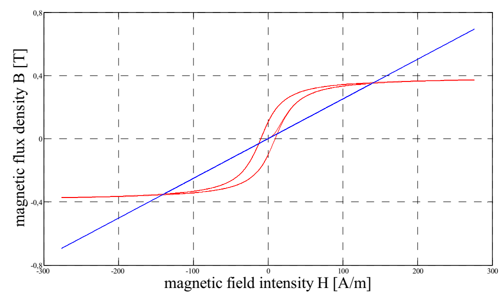

Figure 8 Linear and Nonlinear Hysteresis

The calculated torque of the RRSRM is a function of the magnetic reluctance network, especially of the flux linkage and rotor position as can be seen in following equation.

$$W_{mag} = f(\psi, \varphi)$$

It is not possible to find a simple relation between the resulting torque and the applied current. In fact, the nonlinear behaviour of the magnetic flux linkage must be considered as can be seen in Figure 9.

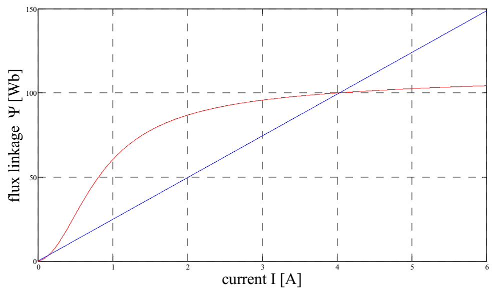

Figure 9 Magnetic flux linkage

The magnetic flux linkage is a nonlinear function of the supplied current. Therefore, the inductions have a nonlinear behaviour and affect the function of a rolling rotor switched reluctance motor. The nonlinear relationship is illustrated by the equation below and it can be determined by means of the characteristic curve of Figure 9.

$$L = \frac{\psi(I)}{I}$$

5.1. Torque Calculation

The calculation of the torque is carried out on the basis of magnetic co-energy. The total energy $\Psi_0 I_0$ is composed of magnetic field energy and magnetic co-energy as is illustrated in Figure 10. The magnetic co-energy has no physical relevance and it is only used for the calculation of the torque. Therefore, the magnetic co-energy cannot be measured directly [5].

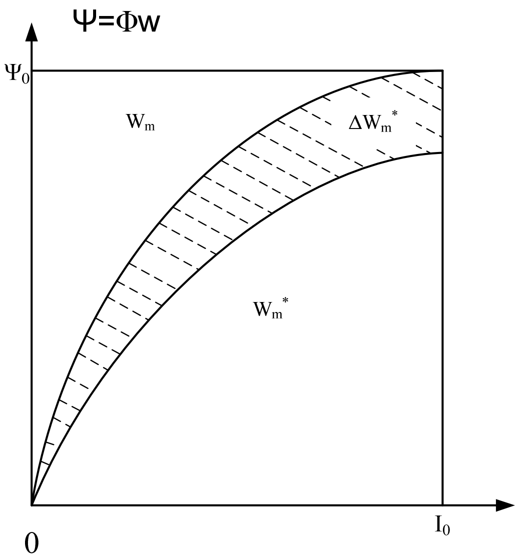

Figure 10 Calculation of Co-Energy

The magnetic co-energy is used for the determination of the mechanic energy which arises due to the rotation of the rotor.
The input energy of one phase can be calculated using the following equation:

$$\int u \cdot i \, dt = \int \left(R \cdot i + \frac{d\psi}{dt} \right) \cdot i \, dt = \int R \cdot i^2 \, dt + \int i \, d\psi$$

If the Ohmic drops are neglected then the equation can be expanded by partial integration as follows:

$$\int i d\psi = i\psi - \int \psi di$$

In the process the magnetic energy can be defined as follows:

$$W_{mag}(\varphi,\psi) = \int_0^{\psi_0} i(\varphi,\psi)\, d\psi$$

and then the magnetic co-energy as:

$$W_{co}(\varphi,i) = \int_0^{i_0} i(\varphi,i)\, di$$

This magnetic co-energy is used for the torque calculation and is presented in the following equation:

$$\tau = \frac{\partial W_m^{*}(\varphi,i)}{\partial\varphi} = \frac{\partial}{\partial\varphi}\int_0^{i_0} \Psi(\varphi,i)\, di$$

These fundamental descriptions show that the nonlinear effects of magnetic material have strong influences on the mode of operation and the torque characteristic of rolling rotor switched reluctance motors. It is not possible to find a simple relation between the resulting torque and the applied current. In fact, the nonlinear behaviour of the magnetic flux linkage must be considered [2].
Furthermore, on the basis of the Jiles-Atherton model the magnetic losses can be calculated in the materials. All these dynamic effects are the basis of further investigations.

6. RESULTS AND CONCLUSION

The paper deals with the construction and functional modelling of rolling rotor switched reluctance motors. Many highlights of such machines were discussed here, emphasizing the background equations in mathematical modelling manner. Furthermore, the mathematical background was analysed which was used for the implementation. Several important equations were explained, especially the importance of distributed and concentrated parameters. The RRSRM has a time- and position dependent reluctance network, the description of which involves distributed parameters. This model description can be seen in the completed implementation. The variable time and position reluctance network generates many influences in the other physical modelling domains. These effects were also illustrated and explained here. Furthermore, in some materials the magnetic field generates electromagnetic phenomena. One phenomenon is the nonlinear permeability of magnetic materials. This property had to be investigated in a way that an exact material model became available, supporting further researches. The nonlinear behaviour was modelled on the basis of the Jiles-Atherton equations. This model describes physical effects in a mathematical way. The behaviour is modelled using differential equations which were explained and presented here. Finally, the description of the magnetic field was illustrated. The implementation on the basis of an electrical network, including all these mentioned mathematical descriptions and analyses using a rolling rotor switched reluctance motor were explained in this paper. Technical details of an experimental implementation were illustrated and explained. These scientific findings will be used for future work.

This paper has shown a multi-domain modelling approach of rolling rotor switched reluctance motors. Such a model description is a solution to analyse a system having components within multiple physical domains. Furthermore, the non-linear properties of reluctance networks were described and modelled. These results have built a technical expertise for future research of RRSRM.

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